AEROTHERMODYNAMIC DESIGN OF JET PUMP FOR A TURBOPROP AIRCRAFT ENGINE IN PUSHER CONFIGUARATION

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Abstract. Engine oil cooling in ground idle condition is a problem area in pusher type turboprop aircraft due to non-availability of propeller slipstream into the nacelle. Therefore, it becomes necessary to induce air flow through the oil cooler by other suitable means. One such idea is the use of a jet pump (or ejector) aft of the oil cooler. However, this imposes additional demand on the compressor bleed air, over and above that required by the Environmental Control System (ECS) for cabin air. This paper describes the aero-thermodynamic considerations used for design of a jet-pump in one such application along with test results. Sample calculations have been presented for a typical jet-pump used in the oil cooling system of a pusher type turboprop engine aircraft. The calculations have been compared with the experimental results. The results obtained show that the design objectives are met and this design allows simultaneous operation of oil cooler and ECS.

Keywords: Ejectors, engine, pressure ratio, jet-pump

1 Introduction

Adequate cooling is essential to maintain the engine operating temperatures within limits as prescribed by the Original Equipment Manufacturer (OEM), and to ensure satisfactory operation of the engine and its accessories. A means of cooling the engine oil must be provided and a suitable oil cooler should be selected for the purpose. On certain aircraft configurations, oil cooling may be limited during ground operations. This is due to lower engine power settings, which do not provide sufficient propeller slipstream (or entrainment as in 'pusher' type aircraft) to supply adequate air flow through the oil cooler. In such cases, engine compressor bleed air can be used to drive an ejector, which increases air flow through the oil cooler. Jet pumps are often preferred in the applications where low pressure ratios are required or where corrosive fluids or hot gases are handled. They are commonly used in aircraft air conditioning systems, oil cooling system, low pressure testing of gas turbine and ram-jet combustion chamber etc. Design knowledge on jet pump is limited, primarily due to a large number aero-thermodynamic variables associated with the analysis. In the majority of the practical applications, ejectors are made of two co-axial nozzles. A high-pressure fluid (the driving or primary fluid) enters the primary nozzle, where it expands to

adfa, p. 1, 2011.

produce a high velocity jet. This entrains low-pressure fluid (the secondary or induced fluid) at its boundary, and the two fluids are then combined in the mixing chamber of the ejector. Sample calculations have been presented for a typical jet-pump used in the oil cooling system of a pusher type turboprop engine aircraft. Design calculations have been compared with the experimental results and found satisfactory.

2 Aero-Thermodynamic Design

2.1 Test Case and Assumptions

The jet pump is designed with the following engine operating conditions and with appropriate assumptions.

Engine operating condition:

Flight idle: Bleed air limit: 12 Lb/min per engine
Bleed air pressure, P3 : 38 psia (Flight Idle); 23 psia (Ground Idle)
Bleed air temperature, T3: 885 ^{o}R (Flight Idle); 713 ^{o}R (Ground Idle)

Assumptions: Refer Fig.1

- The bleed air required for Environmental Control System (ECS) is 7 lb/min/engine and therefore the bleed available for ejector is limited to a maximum of 5 lb/min per engine.
- Test Condition is for both ECS and Ejector ON.
- Ambient condition: Altitude: 3000ft, OAT = ISA+35°C.
- Isentropic flow of both primary and secondary streams up to plane 2.
- Uniform static pressure distribution in plane 2.
- Constant area of primary and secondary streams with sub-sonic conditions in plane 3.
- The empirical relation for efficiency of the mixing section is based on the tests conducted on various jet pumps having varied geometrical parameters.

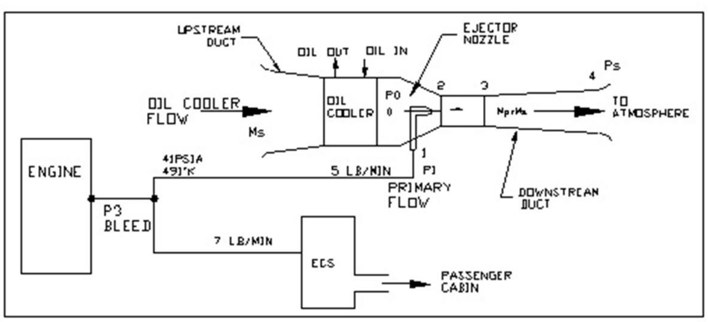

Fig. 1. Schematic Line Diagram of Ejector System

2.2 Heat Rejection Capacity of Oil Cooler

The required heat rejection capacity of the oil cooler and the corresponding air flow through the oil cooler was estimated as follows.
Engine Power=25 SHP. (Ground Idle, based on torque measurement)
Oil temperature at oil cooler inlet = 221 °F (105°C)
Ambient temperature = 120°F (49 °C; ISA+35
Oil flow=150 ppm.

From the data given by the engine manufacturer (Fig.2), the rate of heat rejection by the engine (HR) is 1000BTU/min. The corrected heat rejection rate by using the heat capacity of the oil (HCoil) at maximum oil temperature is:

$$HC_{oil} = 5.96E^{-4} \times \left(OT_{\max} + 670\right) = 5.96E^{-4} x \left(221 + 670\right) = 0.531\, BTU / lb^{o} F \quad (1)$$

Assuming that all the heat rejected from the engine is rejected from the oil cooler, we can say that $HR_{engine} = HR_{cooler}$. The temperature drop of the oil through the oil cooler (φOT_{OC}) can then be calculated as:

$$\Delta OT_{oc} = \frac{HR_{cooler}}{W_{oil} \times HC_{oil}} \quad (2)$$

$$\Delta OT_{oc} = \frac{1000}{150 \times 0.531} = 12.6\ °\text{F} \quad (3)$$

The oil inlet temperature of the oil cooler ($OT_{OC,\ inlet}$) is then calculated as:

$$OT_{oc,\ inlet} = OT_{\max} + \Delta OT_{oc} \quad (4)$$

$$OT_{oc,\ inlet} = 221 + 12.6 = 233.6°\ \text{F} \quad (5)$$

The heat rejection of oil cooler is normally expressed as:

$$HRC = \frac{HR_{cooler}}{\left(OT_{OC,inlet} - AT_{OC,inlet}\right)} \quad (6)$$

Required Standard Heat Rejection Capacity (SHRC) of the oil cooler (BTU/MIN/100°F) is

$$SHRC = \frac{1000 \times 100}{\left(233.6 - 120\right)} = 880\ \text{BTU/min/100°F} \quad (7)$$

Using the characteristics of the oil cooler and the SHRC calculated above, the minimum airflow required ($W_{OC,air}$) was estimated as 50 Lbs/min with an associated air flow pressure drop of 0.61 in H_2O (corrected). The actual pressure drop being 0.6/ů =0.6/0.85=0.72 in H_2O.

2.3 Ejector Design and Test Results

Ejectors are devices used to induce flow through ducts. In majority of practical applications; ejectors are made of two coaxial nozzles. A high pressure fluid (the driving or primary fluid) enters the primary nozzle, where it expands to produce a high velocity jet. This entrains a low pressure fluid (the secondary or induced fluid) at its boundary, and the two fluids are then combined in the mixing chamber of the ejector. The study of ejector design is mostly experimental or semi analytical studies usually based on one dimensional model. It is noted that for a given primary nozzle geometry, the ejector performance strongly depends on the three following geometric parameters: the secondary-to-primary throat area ratio, the length of the mixing chamber and the distance of the primary nozzle exit from the mixing chamber inlet. Following are the design constraints:

Primary mass flow, Mp not exceeding 5lb/min
Primary pressure, P3 =30.5 psig (avg.)
Bleed air temperature, T= 784 °R (436 K)
Required flow through the duct: 50 lb/min (approx.)

For flow evaluation and testing, a three-tube, twelve-nozzle ejector with holes of 3.1mm diameter (Fig.3) was considered. Following procedure was adopted to estimate the mass flow through the ejector:

At standard temperature and pressure (STP) conditions, for an assumed mass flow of 3.6 lb/min, the losses in the supply line, bends, ejector inlet, inlet bends, common rail, manifold, nozzle, shut-off-valve were estimated (using Ref.1) as 8.3 psi. The exit dynamic pressure was estimated to be equal to 5.3 psi leading to a net pressure differential of 13.6 psi. The P3 port pressure and temperature conditions are as below as an average of Flight Idle (F.I) and Ground Idle (G.I) conditions:

P3=30.5 psia; T3= 784 °R
Ʀ = density ratio (ISA+35, S.L) = 0.598

Therefore available ǻφP = 0.598 x (30.5-14.7) =9.45 psig; hence the corresponding mass flow under ambient conditions is estimated as:

$$\sigma \Delta P = \Delta P_{std} \left(\mathrm{w} / \mathrm{w}_{std} \right)^2 \Rightarrow w = \mathrm{w}_{std} \sqrt{\sigma \Delta P / \Delta P_{std}} \quad (8)$$

or $w = \mathrm{w}_{std}\sqrt{\sigma\Delta P/\Delta P_{std}} = 0.06\times\sqrt{9.45/13.6} = 0.05\,lb/\sec = 3.0\,\mathrm{b/\min}$ (9)

Now, the above estimated flow through the ejector was óverifiedô using the Petrovsky formula (Ref.2):

$$w = KC_d A p_{1t} N\Big/\sqrt{T_{1t}} \tag{10}$$

Where

- w = gravimetric flow (lb/sec)
- $K = 1.2855\sqrt{g/c_p} = 0.53033$
- cp = specific heat at constant pressure
- Cd = discharge coefficient
- A = throat area (sq.in)
- P1t= absolute total pressure (high side)
- T1t= absolute total temperature (high side)
- N = restriction factor or ósub-critical flow factorô

The restriction factor is a function of the pressure ratio (high-side to low-side) and was read from the tables presented in Ref.2. In order to arrive at the pressure ratio, the previously estimated pressure loss up to the ejector hole (8.3 psi) under STP conditions was corrected for the expected mass flow:

$$\sigma\Delta P = \Delta P_{std}\left(\mathrm{w}/\mathrm{w}_{std}\right)^2 = 8.3\left(0.05/0.06\right)^2 = 5.76\,\mathrm{psig}$$

Therefore,

$\Delta P = 5.76/0.598 = 9.64\,\mathrm{psig}$

P1t = 30.5-9.64=20.86 psig;   P1t/p2=20.86/14.7=1.42

and N = 0.9293 and flow per hole:

$$w = KC_d A p_{1t} N\Big/\sqrt{T_{1t}} = 0.53033\times 0.9293\times C_d\times 0.0117\times 20.86\sqrt{784} \tag{11}$$

Assuming a discharge coefficient of 0.8 the above expression gives the flow per hole as 0.00344 lb/sec and for twelve holes the flow is 0.041 lb/sec which is equal to 2.46 lb/min.

Earlier several nozzle configurations had been bench tested (Table-1) with the oil-cooler duct to evaluate performance and to evaluate secondary to primary flow ratios. Based on the test results it was felt that with a tube ejector consisting of multiple tubes with holes drilled perpendicular to the tubes a mass flow ratio of up to ~ 20 could be achieved. Therefore, with a primary flow of around 2.5 lb/min, a secondary flow of 50 lb/min was expected for this ejector configuration which consisted of three tubes with four holes each of diameter 3.1 mm.

2.4 Description of test setup

This tube ejector configuration was tested on a test rig along with the oil cooler to ascertain the induced mass flow. The test setup (Fig.4 & Fig.5) consisted of a primary pressure line which supplied the air (acts as engine P3 line) to the ejector, a differential pressure transducer which measured delta pressure across the oil cooler and two pressure indicators which displayed the primary and differential pressures. At around 35 psi primary pressure, the mass flow through the duct was estimated as 46 lb/min using the measured oil cooler pressure drop characteristics.

3 Conclusions

The final testing was done on the aircraft with the engine running at flight idle condition and ECS on at 3000 ft altitude and ISA + 20^{o}C. The pressure drop across the oil cooler was measured along with the P3 port pressure and temperature. The estimated flow through the duct using the oil cooler pressure drop characteristics was 47 lb/min and the oil cooling was found to be satisfactory, as indicated by the oil temperature. Moreover, the ejector design allows parallel operation of oil cooler and ECS which was not possible with the previous standard design of ejector used in the system.

4 Acknowledgements

The authors wish to thank all partners and associated partners for their contribution to the program and for their permission to publish this paper.

5 References

1. Thermodynamics of Incompressible and Compressible fluid flow, SAE AIR 1168/1.
2. Calculation of Flow of Air and Diatomic Gases, Chester W. Smith, General Electric Company, 1945.

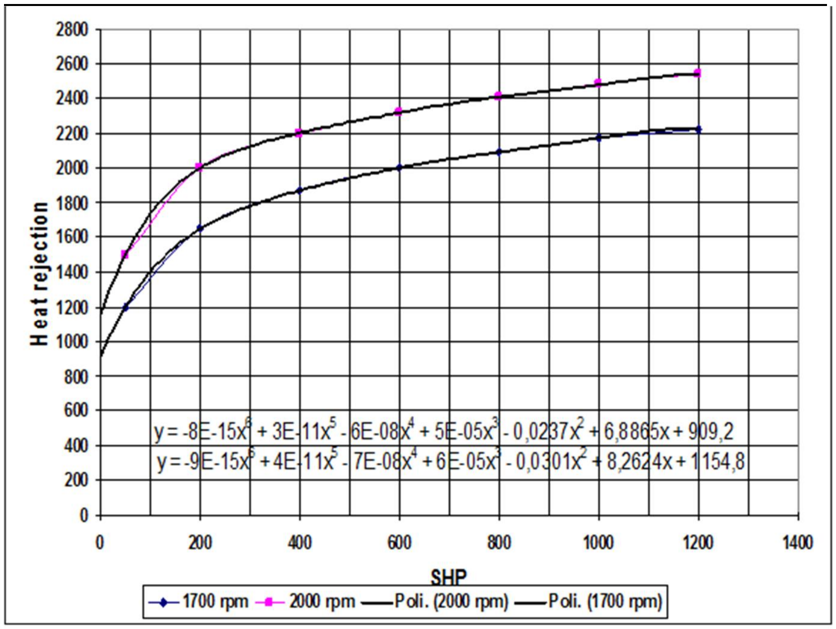

Fig. 2. Graph to Estimate the Heat Rejection at Zero Power

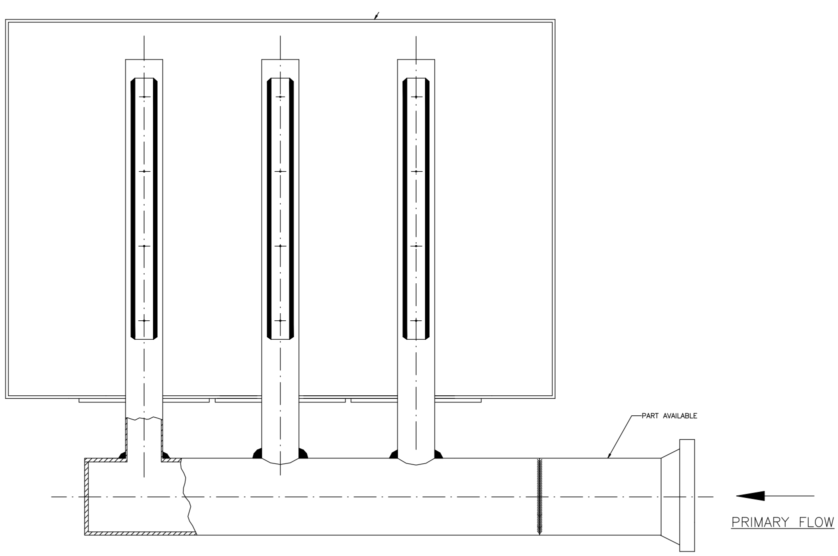

Fig. 3. Selected Ejector Geometry

Table 1. Test Results on Different Ejector Configurations

CONFIGURATION	AREA	mdot	Primary mass flow	Secondary mass flow	Ms/Mp Ratio
	(sq.in)	(kg/sec)	(lb/min)	(lb/min)	
Slotted tube : 42 slots	0.374	0.077262	10.22	49.5	4.8
Bident: 8 holes	0.1723	0.035594	4.71	47	10.0
Bident: 4 holes	0.1723	0.035594	4.71	47	10.0
Three-nozzle	0.1059	0.021877	2.89	36.5	12.6
Bident : 10 holes	0.0557	0.011507	1.52	30.7	20.2

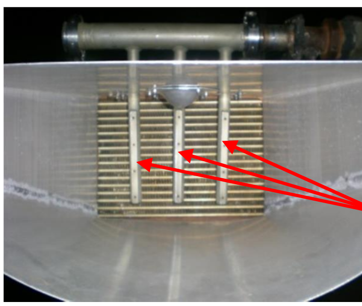

Fig. 4. Ejector Nozzles

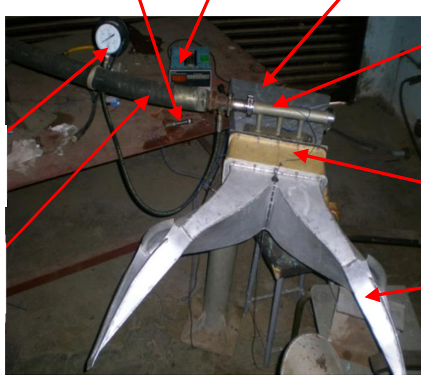

Fig. 5. Test Set up